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INVESTIGATING METAL-CUTTING PROCESSES:
V. FOUNDATION AND EVOLUTION OF THE PRINCIPLES OF HIGH-SPEED CUTTING OF METALS

Docent M. Klushin

The majority of investigations of the metal-cutting process, up to a certain time, had one very essential shortcor .g: properties of the machined material were considered as given properties and unchangeable. The fact that the properties of metal vary with a change of cutting conditions, especially cutting speed, was not taken into consideration.

Engineers at the Kiev Red Banner Plant were the first investigators who clearly evaluated the effect of the cutting speed on the cutting process. In 1937, this group of engineers introduced and experimentally substantiated the theory of machining steels hardened higher than Rockwell C 60.

According to this theory, machining of hardened steels is based on the fact that high cutting speed develops, at the point of contact of the cutter with the machined object, a high temperature which has a softening effect on the metal before the cutting. Since the hard-alloy cutter loses its hardness to a lesser extent than the hardened steel, it is possible to create, by varying the cutting speed, a temperature at which the difference between the hardness of the cutter and the steel will be at a maximum. Obviously, the machining of hardened steel must be conducted at the highest possible cutting speed which will produce a maximum cutting temperature, but not higher than the critical temperature at which the cutter loses its hardness and, consequently, its endurance.

The machining of hardened steels during experiments in the Kiev Red Banner Plant was performed on a lathe with cutters which had tips made of four hard alloys: RE-6 (tungsten-cobalt), RE-8α21 (titanium-cobalt) and "sergonit." The cutters with tips made of α-21 and "sergonit" crumbled at the beginning and therefore the basic experiments were conducted with tips made of RE-6 and RE-8.

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The rake angle of cutters varied from $+5^{\circ}$ to -15°. Grinding of cutters with a rake of $+5^{\circ}$ and -15° showed poor results: the cutters were crumbled at large positive rakes, and excessive cutting forces were obtained by large negative rakes. Chips were obtained very hot and completely annealed. The machined surface was smooth with a polished appearance. No structural transformation was detected on finished surfaces.

A. V. Alekseyev conducted experiments on turning stainless steel 18/2 with various degrees of hardening. The cutters had tips made of RE-8 alloy. ("On the Problem of Cutting Hardened Steels at High Speeds," Vestnik metallopromyshlennosti, No 1, 1939.)

According to the experiments by Alekseyev, the endurance of the cutter decreases as the cutting speed of hardened stainless steel is increased, while according to data obtained by engineers of the Kiev Red Banner Plant the reverse takes place. This difference was explained by Alekseyev as the result of different trends of structural transformations in steels. In carbon steels, transformations proceed in the direction of martensite-troostite-sorbite. This transformation trend is favorable for cutting. In high-alloy steels, martensite transforms with elevation of temperature into austenite, and this phenomenon has an unfavorable effect on the cutting process because of the poor machinability of austenite.

In addition, transformation rates must be taken into consideration. Changes in the physical properties of heated steel are caused by transition of the space lattice into another type of lattice. This rearrangement proceeds at different rates in various metals, and the transformation rates of alloy steels are lower than those of carbon steels. There are reasons to assume that these rates lag considerably behind the cutting speed. Therefore, it is quite possible that the metal layer to be removed by the tool, in contact with the cutter for an extremely short period, does not change its physical properties although it can be heated.

L. M. Reznitskiy experimented with machining hardened chrome-nickel steels, as reported in the chapter "Machinability of Hardened Alloy Steels," in Materialy k konferentsii po rezaniyse metallov (Materials for the Conference on Metal Cutting), LONITOMASh (Leningradskoye otdeleniye nauchnoye inzhenerno-tekhnicheskoye obshchestvo mashinostroyeniya, Leningrad Division of Scientific Engineering Technical Society of Machine Building) 1940, and proved the possibility of high-speed cutting for very hard steels using hard-alloy cutters with negative rake angles. He found that cutting is possible at 40-125 meters per minute and that the optimum rake angle is $\gamma = -5^{\circ}$.

At approximately the same time, Professor V. A. Krivoukhov and Docent P. P. Grudov also studied the problem of cutting hardened metals, in particular "khromansil" (chrome-manganese silicon steel).

These investigators also came to the conclusion that metals, earlier considered as not subject to cutting, may be machined at 50-60 meters per minute under the condition that hard-alloy cutters with negative rakes are used.

The significance of using negative rake angles was explained as follows: in the case of a positive rake, the cutter tip works for bend and shear, i.e., it is subject to deformations to which its resistance is least satisfactory, especially in the case of impact load; at a negative rake, the hard alloy tip is mainly subject to compression, the deformation which hard alloys resists best; and in a considerably less degree, it is subject to bend and shear.

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During 1940, the problem of high-speed and superhigh-speed cutting of metal was widely discussed in Soviet technical literature. The main stimulus for such an interest in the subject was the publication of V. D. Kuznetsov's considerations on the possibilities of metal superhigh-speed cutting and the initial results of machining at speeds up to 1,500 meters per minute (V. D. Kuznetsov, "Possibility of Using Superhigh Speeds for Steel Machining," Zhurnal tekhnicheskoy fiziki, No 5, 1940; Ye. P. Nedeinskaya, "Application of Superhigh Speeds for Cutting Metals," Vestnik metallopromyshlennosti, No 3, 1940).

V. D. Kuznetsov arrived at the idea of the possibility for using superhigh speeds in metal cutting by applying to metals the results of his investigations on plasticity and strength of solids under static and dynamic loads.

The theoretical deliberations of Kuznetsov are as follows:

The work performed during cutting consists of four parts:

$$A = A_{disp} + A_{pl\ d} + A_{fr} + A$$

The first part, A_{disp}, is the work used for transferring a certain number of molecules from the inner parts of a machined body to the surface, i.e., the dispergation work connected with the surface increase. Referring to the works by Gardin and Bessonov, who established in their investigations of rock-salt crystals the negligible magnitude of A_{disp} in respect to total work used for cutting, Kuznetsov considers that A_{disp} may be disregarded.

The second part, $A_{pl\ d}$, is the work used for plastic deformation of the metal in front of the cutter and under it.

The third part, A_{fr}, is the work consumed by friction in metal cutting and is used for dispergation and plastic deformation.

Hence: $$A_{fr} = A'_{disp} + A'_{pl\ d}$$

The fourth part, $A_{el\ d}$, is the work used for elastic deformations and converted, in the final result, into heat.

Parts A'_{disp} and $A'_{el\ d}$ may be added to A_{disp} and $A_{el\ d}$, respectively, and then:

$$A = A_{disp} + A_{pl\ d} + A_{el\ d}$$

But since the value of A_{disp} may be neglected, finally we will obtain:

$$A = A_{pl\ d} + A_{el\ d}$$

Kuznetsov assumes that in the process of cutting plastic metals, such as lead, tin, copper, aluminum, iron, and soft steel, $A_{pl\ d}$ has predominant significance, but in the case of cutting brittle metals, as cast iron and hardened steel, the main role belongs to $A_{el\ d}$.

In his attempt to find a possibility for decreasing the $A_{pl\ d}$ component in machining plastic materials, Kuznetsov refers to the results of work by A. F. Ioffe and co-workers who determined, by X-raying, the yield strength of rock salt in respect to temperature. They established that the yield strength decreases as the temperature increases and approaches zero at the melting point, whereas the tensile strength remains constant and does not depend on temperature. Rock salt under tension at temperatures less than 200° breaks without plastic deformations and behaves as a brittle body. But at temperatures higher than 200°, the yield strength is reached first, plastic deformations take place, and only then does rupture occur. But the yield strength depends not only on temperature, but also on the rate of deformation; it increases as the rate of deformation increases.

Finally, Kuznetsov suggests that the best method for decreasing the force $A_{pl\ d}$ used for plastic deformations is cutting at superhigh speeds, i.e., at speeds of several thousand meters per minute. The higher the cutting speed, the lower the plastic deformation and the smaller the amount of heat.

Numerous experimental attempts by various investigators to substantiate Kuznetsov's theories failed and he came to the conclusion that the metal remained in plastic state at all speeds, up to 6,000 meters per minute, used in experiments, and that the endurance of cutting tools at speeds over 2,000 meters per minute is practically zero.

Kuznetsov's work stimulated further theoretical and experimental works on the problems of the cutting process.

L. T. Mendeleyev studied the effect of the cutting angle and speed on the contraction of a lead chip. Experiments were conducted at speeds from 30 to 1,063 meters per minute with cutters, the cutting angles of which varied from 32 to 76 degrees.

Mendeleyev observed a decrease of chip contraction with an increase in cutting speed up to a certain limit, above which a further increase in cutting speed did not involve any change in contraction of the chip. He proved that this critical value of the cutting speed depends on the cutting angle: the lower the cutting speed, the smaller the cutting angle, i.e., the larger the rake angle.

It follows from Mendeleyev's data that contraction of the chip increases with an increase in the cutting angle. This observation was supported by numerous data of other investigators. However, the data led to an essentially new conclusion, i.e., the influence of the cutting angle on contraction decreases with the increase of the cutting speed.

On the basis of his experiments, Mendeleyev came to the conclusion that by increasing cutting speed, it is possible to increase the cutting angles of tools, i.e., their rake angles may be decreased.

Several workers of the Siberian Physicotechnical Institute (K. V. Savitskiy, P. D. Krivopalov, G. S. Yarkina) investigated the effect of the temperature of preheating a material being machined on the chip contraction and cutting coefficient.

Experiments conducted in the institute on machining copper, lead, and tin demonstrated that with an increase in preheating, temperature chip contraction decreases and this decrease is more noticeable with increase of the cutting angle. The coefficient of cutting decreases still more greatly than contraction of the chip, as the preheating temperature is increased.

In 1944, Professor A. I. Kashirin published his monograph Issledovaniye vibratsiy pri rezanii metallov (Investigation of Vibrations in Metal Cutting), Academy of Sciences USSR, 1944. Kashirin studied the effect of cutting speed on components of the force of cutting. The viewpoint had long been accepted that the speed of cutting had practically no effect on the cutting force. This was correct, taking into consideration that the investigators did not use cutting speeds beyond the range of 25-30 meters per minute. Kashirin's investigations differed from earlier works in the range of cutting speeds and in the application of inertialess electrical instruments for measuring both components of the cutting force.

Kashirin's basic conclusions are expressed in the following statements:

1. In cutting brittle metals, e.g., cast iron, the average value of the cutting force does not depend on the cutting speed.

2. In the case of cutting steels with a sufficiently high content of carbon, 0.5% and over, the force of cutting has a slight tendency to decrease with an increase in the cutting speed. Practically, it may be assumed that the cutting force does not depend on the speed for such steels.

3. Formation of elements of the chip and related variations of the cutting force are not entirely periodical in cutting tough steels with very low speeds and heavy chips.

4. Affirmation of the cutting force's independence of the cutting speed is wrong in the case of tough steels. In this case, the cutting force undergoes a comparatively sharp ascent to the maximum value and then a slow decrease at a certain range of cutting speeds, the range being determined by the cutting depth, feed, and shape of the cutting tool.

5. In a certain range of speeds, the force of cutting tough steels becomes highly unstable. Maximum deviations of cutting-force components from their average values were observed at a cutting speed appropriate to the maximum average value of the components.

Experiments for high-speed turning of machine steels using cutting tools with positive and negative rakes were conducted by M. I. Klushin and E. I. Feldshteyn ("Influence of Cutting Speed on the Cutting Force in the Case of Using Tools With Positive and Negative Rakes," Stanki i instrument, No 7-8, 1944).

Observation of the appearance of steel chips removed by cutting tools with positive and negative rakes ($\gamma = +20^\circ$, $+10^\circ$, 0°, -10°, -20°) shows that an increase in cutting speed causes an increase in the radius of chip curls. Chips of cross section $t \times s = 3.0 \times 0.1$ have the appearance of tightly curled spirals of Archimedes if they are cut off by cutters with positive rakes at low speeds, about 20 meters per minute. With increase in cutting speed, the chip acquires the shape of a continuous spiral ribbon, the curl diameter of which increases from 15-20 mm at speeds of the order of 100 meters per minute to 50 mm at speeds of the order of 300 meters per minute. The color of the chips gradually changes from light-steel to blue. In the case of using cutters with negative rakes at low speeds of the order of 20 meters per minute, chips are obtained in the shape of small curls. At high speeds, the chip has the appearance of a continuous ribbon, the curl radius of which increases considerably faster than in the case of cutters with positive rakes. At a negative rake of -10° and cutting speeds over 200 meters per minute, the chip has the shape of a straight nonspiral ribbon. At a feed greater than 0.1-0.3 mm and low cutting speeds of 40-50 meters per minute, the chip removed by the tool with a negative rake is divided into separate elements, i.e., represents a typical structure of shearing.

Experiments for studying the variation of cutting force relative to the cutting speed were conducted with steel 50 under the condition of free cutting at a feed of 0.1 mm per revolution using cutting tools with rakes of $+20^\circ$, $+10^\circ$, -10° and 0° and with clearance of 3°.

Results of these experiments led to the following conclusions:

1. When using cutting tools with positive rakes, an increase of cutting speed causes an increase in the tangential force of cutting.

2. When using tools with a zero rake, a cutting speed in the range from 50 to 350 meters per minute has no effect on the value of the tangential cutting force.

3. In the case of negative rakes, an increase of cutting speed in the range from 50 to 400 meters per minute involves a decrease in the tangential cutting force.

4. The value of the cutting speed at which cutting forces become equal for tools with either positive or negative rakes amounts approximately to 400 meters per minute.

5. In the cutting speed range from 10 to 40-50 meters per minute, when using tools with positive and negative rakes, a great scattering of experimental data takes place, but a general tendency toward increase of cutting forces with increase of cutting speed was observed.

Experiments by several other investigators corroborate in general the above-mentioned regularities in high-speed turning of machine steels are shown in Skorostnyye metody obrabotki metallov (High-Speed Methods of Machining Metals), Mashgiz, 1948.

Data of particular interest are given in the work of Professor V. A. Krivoukhov and his co-workers. Docent B. Ye. Brushteyn, Docent S. V. Yegorov and Engineer D. N. Kozlov, in the chapter, "Superhigh-Speed Metal Cutting and Conditions for Its Realization" in Skorostnyye metody obrabotki metallov, Mashgiz, 1948.

After a series of investigations, these authors established that, in the case of using cutters with negative rakes and ordinary values of tool angles (φ 60 ÷ 75°, $\varphi_1 = 10 \div 20°$), temperatures of the cutter, chip, and machined part rise with the increase of cutting speed.

However, the temperature of the chips, i.e., the layer being cut off is lower than that of the cutter.

To further increase the cutting speed, they attempted to find a shape for cutting tools which would provide for still greater evolution of heat. This was achieved by sharply decreasing tool angles.

New type-KBYeK cutters (trade name composed of initial letters of Krivoukhov, Brushteyn, Yegorov, and Kozlov) have γ -5°, $\varphi = 10 \div 20°$, $\varphi = 10°$ and $r = 0$.

The most valuable property of KBYeK cutters is that the temperature on their cutting edges is lower than the temperature of the layer being cut off.

Thus, the cutting edges, even at speed of 250 meters per minute, have a temperature of 750°, i.e., below critical temperature, when the removed layer reaches a temperature of 850°, which is already in the softening zone of high alloy steels.

Contraction of the chip in machining with the KBYeK cutter is less than in operation with ordinary cutters. Thus, with a change in cutting speed from 20 to 100 meters per minute the longitudinal contraction varies from 2 to 1.42 for the ordinary high-speed cutter and from 1.55 to 1.25 for the KBYeK cutter and even reaches 1.1 at a cutting speed of 250 meters per minute.

Application of KBYeK cutters permits an increase in cutting speed 2-4 times over the speeds established for ordinary cutters with negative rakes.

Theoretical and experimental investigations by Soviet scientists permit formulation of the fundamentals of high-speed metal cutting.

The process of chip forming is a process of successive, more or less intensive shifts of metal layers in the direction of the shear angle β_1.

Resistance of machined material to cutting and the type of chip formed depend on the absolute value and ratio of resistance of material to crushing, shearing and break and, on the other hand, on the value of β_1. (M. I. Klushin, "Negative Rake of Cutting Tools," Stanki i instrument, No 1, 1946).

A continuous chip is formed at comparatively large angles of shear β_1 when the area of shifting, being determined by formula $S_{sh} = \frac{S_o}{\sin\beta_1}$, is comparatively small. Here, S_o is the area of cut in square millimeters and S_{sh} is the area of shifting. The cutting tool, after contact with the material being machined, first causes its compression to a certain extent. However, with further increase of acting force, a certain very thin layer of metal slips along the angle β_1.

The chip of shear is formed at smaller values of β_1 when the area of shifting is considerably larger. The force acting on a tool is insufficient to produce slipping of a certain layer of the metal, and compression progresses. However, with further penetration of the cutting tool, the stressed state in the machined metal changes in such a way that the flow line changes its direction and deformations are developed in a greater and greater region. Finally, at a certain value of the increased acting force, shearing of the chip elements occurs in a direction determined by the shearing angle β_1.

The chip of break is formed in cases when the area of shifting is very large. Chip formation occurs not under the action of shearing stresses but is caused by the normal stresses of breaking away with preliminary formation of a crack along the surface being machined.

The maximum theoretical value of the shearing angle β_1 is determined by the formula

$$\beta_1 = 45 + \frac{\varphi}{2}$$

In practice, the angle β_1 is always smaller than its value as determined by this formula. Deflection of the actual shearing angle from its maximum possible value increases as the ratio between the force of friction F on the front side of the tool and the area of cut S_o increases.

Increasing the speed of cutting causes an increase in the shearing angle β_1, since, because of increased heating of the metal in front of the cutting tool, the actual resistance of the metal to shear decreases. This leads to decreasing normal pressure of the tool against the metal layer and chip and, consequently, the friction force F decreases and also the ratio $\frac{F}{S_o}$.

Increase of the angle β_1 involves a decrease in contraction of the chip and, at small positive or negative rake angles, a decrease in cutting forces.

When using cutting tools made of high-speed steel, the only method for facilitating formation of chips is increasing the rake angle, since the red hardness of high-speed steels is limited. But, when using tools with hard-alloy cutting edges, this may be achieved by increasing the cutting speeds.

Increasing the cutting speeds has an effect on the cutting process similar to that of the rake increase. Therefore, high cutting speeds make possible and also expedient the application of tools with negative rakes.

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